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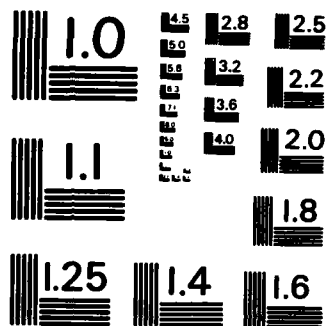
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DEPARTMENT OF DEFENCE
DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION
MATERIALS RESEARCH LABORATORIES
MELBOURNE, VICTORIA

REPORT

MRL-R-924

**THE EFFECT OF INJECTION MOULDING PROCESSING PARAMETERS
ON THE ENVIRONMENTAL STRESS CRACKING RESISTANCE
OF POLYCARBONATE MOULDINGS**

R.J. Roseblade

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ABSTRACT

The effect of injection moulding processing variables on the environmental stress cracking performance of Lexan[®] polycarbonate grades 121 and 101 has been studied. Grade 121 is a general purpose easy flowing grade whilst grade 101 is a high viscosity, high molecular weight grade. A solution of 50:50 by volume toluene/iso-octane was applied as a stress cracking agent and a tensile impact tester was used to determine the strength of the mouldings after immersion in the solvent.

For Lexan[®] 121 it was found that the combination of a heated die (80°C) and a long cycle time (38 s) produced mouldings with superior environmental stress cracking resistance compared to a cycle where the die temperature was 18°C and the cycle time 26 to 27 s.

For Lexan[®] 101 use of the minimum recommended barrel temperature profile resulted in mouldings with superior environmental stress cracking resistance compared to those produced by a cycle using maximum temperature settings. However, if a low injection speed was used in combination with the high temperature settings, then mouldings with a comparable performance to those from the low temperature cycle were produced.

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TABLE OF CONTENTS

	<u>Page No.</u>
1. INTRODUCTION	1
2. EXPERIMENTAL	3
2.1 Materials	3
2.2 Injection Moulding	3
2.3 Environmental Stress Cracking Tests	4
2.4 Tensile Impact Testing	4
2.5 Tensile Testing	5
2.6 Examination of Stress Patterns	5
3. RESULTS AND DISCUSSION	5
3.1 Tensile Testing	5
3.2 Environmental Stress Cracking Tests and Tensile Impact	5
4. CONCLUSIONS	7
5. RECOMMENDATIONS	8
6. ACKNOWLEDGEMENTS	9
7. REFERENCES	10

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PREFACE

This study was carried out at the Royal Melbourne Institute of Technology (RMIT) as a special student project forming part of the "Plastics Higher Technician" course. The project needed to be completed during the academic year at RMIT (2 hours/week) and, as far as possible, using the equipment available there. An exploratory investigation was undertaken on the effects of moulding variables on the environmental stress cracking resistance of polycarbonate mouldings and ~~an~~ ^a method to quantify the effects was developed.

THE EFFECT OF INJECTION MOULDING PROCESSING PARAMETERS
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RESISTANCE OF POLYCARBONATE MOULDINGS

1. INTRODUCTION

Bisphenol-A polycarbonate (Fig. 1) has a high glass transition and melting point, broad temperature usage, rigidity complemented by toughness, resistance to creep and other important properties attributed to its molecular structure [1]. Consequently, it is used extensively as an engineering thermoplastic and in the Defence Industry examples include aircraft transparencies, projectile driving bands, hydrophone mounts, bomblet components, fire extinguisher nozzles, tent pegs, and cases for field telephone sets. However a major disadvantage of this polymer is its propensity for solvent crazing and cracking by a variety of chemical agents.

The terms solvent crazing and solvent cracking refer to the widespread experience of the onset of crazing and even catastrophic failure in the presence of a wide variety of organic agents at stresses far below the critical stresses for crazing and the tensile strengths of the materials tested in air. Solvent cracking of glassy polymers is one member of the diverse class of phenomena generally called environmental stress cracking (E.S.C.) which also includes, for example, ozone cracking of rubbers, water cracking of glass, and hydrogen embrittlement of steel [2].

Two hypotheses have in the past been applied to solvent crazing and cracking in glassy polymers, and currently it appears that both may be required to explain all the features of these phenomena. As applied to crazing, the first hypothesis is that liquids which wet the polymer surface lower polymer surface energy and thus make easier the formation of new surfaces. The second hypothesis is that the aggressive agent swells the polymer more or less, causing a lowering of T_g and thus a reduction of the stress required to cause plastic flow of the polymer at a given temperature [2].

Resistance of polycarbonate to environmental factors such as temperature, water, air, light, acids, bases, solvents and other chemicals is influenced by the crystallinity and orientation as well as by the shape, size and past history of any given sample [3]. Failure of a polycarbonate article due to E.S.C. can often be traced to high residual or "frozen-in" stresses in the moulding. These stresses can result from non-uniform cooling of the item while in the mould, temperature differences between the nozzle and mould, overpacking of the mould cavity during injection hold, orientation, and differential thermal expansion of mouldings containing metal inserts.

Of particular importance is the level of mechanical stress (internal and external) associated with the component. The critical stress may be defined as that stress at which, under a particular set of conditions, stress cracking or crazing is known to start. Testing of polycarbonate mouldings for internal stresses is usually carried out by immersing the item in a test solution for a particular time then examining the article for evidence of cracking or crazing [4,5]. Severe stress cracking agents are active at low levels of stress whilst mild stress cracking agents are only active at higher levels. For instance, ASTM D 471-80 specifies a series of reference fuels made from mixtures of toluene and iso-octane, the former being a severe stress cracking agent and the latter a mild one. Values of critical stress and critical strain have been reported in the literature for a variety of glassy plastics exposed to pure liquids. Usually the values are obtained by applying a known strain to the test piece then applying the liquid for a set time followed by examination for cracking or crazing [6,7,8].

Newcome [1] has investigated the effects of processing conditions on mechanical properties of injection moulded polycarbonate. His report discusses the requirements for processing equipment, drying of the resin prior to moulding and the effects of processing variables such as temperature, cycle time, screw speed and injection speed on the resin.

In the present study, an attempt has been made to correlate various injection moulding machine variables with the E.S.C. resistance of polycarbonate mouldings. In common with other methods cited in the references, the mouldings (small dumb-bell shaped tensile impact specimens) were immersed in a selected stress cracking solution for a fixed time then removed and examined for cracking and crazing. Since the assessment of such observations is subjective, particularly when only small differences exist between samples, tensile impact tests were then carried out on the specimens and significant differences determined by statistical analysis of the results. Tensile impact was chosen as a physical test because impact strength is the most outstanding property of polycarbonate. Furthermore, the small test pieces are convenient for immersing in test solutions and the actual impact test can be carried out quickly thus facilitating the testing of large numbers of specimens.

The results of this initial investigation may lead to an understanding of the effects of moulding variables on the E.S.C. resistance of polycarbonate and a method of quantifying the effects. It is recognized that the results obtained by such a procedure might, to some extent, be only applicable to this particular mould and machine and that further work will be

required to show to what extent the effects apply to the processing of polycarbonate generally.

2. EXPERIMENTAL

2.1 Materials

Two grades of General Electric (GE) 'Lexan®' polycarbonate resin, which is based on bis-phenol A, were used in the study. Grade 121 is a general purpose easy flowing grade whilst grade 101 is a high viscosity, high molecular weight grade which was chosen as being representative of the grade likely to be used in manufacturing polycarbonate sheeting.

Prior to moulding, the resin was spread on open trays to a depth of about 13 mm then dried for two hours in an air circulating oven at 120°C. The effectiveness of the drying was checked by the Tomasetti Volatile Indicator method [9], which involves heating a few pellets to their melting point between glass microscope slides and observing whether bubbles are present, thus indicating moisture in the resin. After drying, the material was stored in air-tight solvent tins and exposure to the atmosphere during moulding was kept to a minimum.

2.2 Injection Moulding

A twin cavity die producing two different dumb-bell shaped specimens per shot was used in the trial. One specimen conformed to the type S tensile impact test piece dimensions of ASTM D1822-79 whilst the other conformed to the type 1 tensile test piece dimensions of AS1145-1972. The configuration of these test pieces is shown in Fig. 2.

Moulding was carried out at the Royal Melbourne Institute of Technology (RMIT) using a 1980 model Johns CP 550 hydraulic injection moulding machine controlled by automatic systems and having a clamp force of 55 tonnes and a shot size of 55g. The machine was initially adjusted so that the cavities were completely filled and the specimens easily ejected without the presence of sink marks or other moulding defects. At this stage of the process a significant processing variable was deliberately altered and the machine allowed to equilibrate (usually after about 20 shots) before a set of 20 to 30 specimens was collected.

For each grade of material, three significantly different sets of moulding conditions were employed as detailed in Tables 1 and 2, the main variables being injection pressure, die temperature, barrel temperature and injection speed. In some cases other minor adjustments were necessary for satisfactory mouldings or for the machine to cycle properly using the new set of conditions.

2.3 Environmental Stress Cracking Tests

A test procedure was developed, after trying various solvent combinations and contact times, which consisted of immersing five tensile impact specimens (representing each batch of mouldings) in a 50:50 by volume toluene/iso-octane solution at room temperature for 5 min. followed by washing for approximately 60 s in ethyl alcohol and drying with compressed air. The specimens were then immediately tested for tensile impact strength as detailed below. Washing with ethyl alcohol did not appear to have any significant effect on the test specimens (no cracking or crazing observed after immersion for 1 min.) but it is recognized to be a mild stress cracking agent for polycarbonate and hence could introduce experimental error if contact times were variable.

The above solvent combination conforms to ASTM D471-80, reference fuel C and was selected because it is active against polycarbonate containing low levels of internal stresses. It has the advantage of a convenient action time (significant effect within 5 min.) with the specimens remaining clear after immersion thus facilitating the visual observation of cracking and crazing. Toluene itself is active at a lower critical stress level but acts too quickly (within 1 min.) and causes whitening of the test specimen. With such a short action time the solvent contact time and subsequent removal procedure would be subject to a high experimental error.

Specimens were tested at 1, 7, 35, 43 and 70 days after moulding to determine whether the ability of the mouldings to withstand stress cracking agents was affected by the age of the mouldings. During this period both specimens and solvents were stored in an air conditioned room (20-23°C).

2.4 Tensile Impact Testing

In an effort to quantify the effect of the stress cracking solution on the specimens, tensile impact tests were carried out according to ASTM D1822-79. The energy to break each specimen was then calculated in kJ/m^2 , using the average cross sectional areas recorded in Table 4, and the fracture mode (whether ductile or brittle) was noted. A Zwick Model 5102 impact tester with a maximum pendulum energy of 4J was used for the testing. This impact level was insufficient to break the control specimens (which were tested at the beginning and end of the trial period) or some of the treated Lexan® grade 101 specimens. This placed an upper limit on the recorded impact figures and may have partly obscured differences between the three Lexan® 101 moulding runs. Subsequently some control specimens, representing both grades of Lexan®, were tested on a Zwick machine with a pendulum energy of 15J. These results are recorded in Table 8 and shown in Figs. 3 and 4 for comparison with the results obtained from specimens treated with the stress cracking solution.

2.5 Tensile Testing

The tensile properties of the large dumb-bell specimens were determined on an Instron Model 1026 test machine to check whether the tensile properties of the polycarbonate had been adversely affected by the various moulding conditions. Testing was carried out to ASTM D638-80 with the specimens being conditioned for 24 h at 24°C and 43% rh prior to test. Distance between the grips was 115 mm, gauge length 60 ± 0.5 mm, extension rate 50 mm/min, chart : cross-head speed ratio 1:1 and full scale load 500 kg.

2.6 Examination of Stress Patterns

An attempt was made to compare the stress patterns in the various moulded specimens using crossed polaroids.

3. RESULTS AND DISCUSSION

3.1 Tensile Testing

The results are summarised in Table 3 which shows that the moulding conditions employed did not adversely affect the tensile properties of the material. Apart from modulus of elasticity, the values obtained were in good agreement with those listed [9] for the particular grades of Lexan®. Modulus values calculated from the load-extension curves of plastics materials may vary from those determined with strain gauges and thus account for the lower values obtained, 1400 to 1500 MPa compared to a quoted value [10] of 2300 MPa.

3.2 Environmental Stress Cracking Tests and Tensile Impact Determinations

All specimens were examined for cracks and crazes after solvent treatment. Slight cracking was evident along the corners of all specimens whilst in some cases this also occurred around the ejector pin marks which were on the wide section of the test piece held between the grips during testing. There did not appear to be any relationship between these observations and the subsequent tensile impact performance of the specimens.

Table 5 summarizes the above testing for specimens produced from Lexan® grades 121 and 101 and covers intervals of 1, 7, 35, 43 and 70 days from the date of moulding. This information is shown graphically in Figs. 3 and 4 which indicate the tensile impact results for the various moulding runs against the moulding age in days. The comparative distribution of the tensile impact results is shown in Fig. 5 whilst Table 6 gives a statistical analysis of the tensile impact figures and shows the probability of the observed differences occurring by chance alone.

A number of factors complicate the interpretation of these results.

Firstly, the tensile impact method in common with other methods of determining impact strength has a high inherent variability as shown by the range of results produced when five apparently identical specimens were tested. (The vertical lines in Figures 3 and 4 represent the range of results which occurred for each series of measurements).

Secondly, the upper limit placed on the recorded figures by the limited impact of the test machine would partly obscure any differences between the three Ilexan® 101 moulding runs. Subsequently, some idea of the tensile impact strength of control specimens was obtained by testing on a larger machine (Table 8).

A third factor which contributed to variability of the results was the mode of fracture of some samples. The specimens from run 5 were clearly in a transition zone where the polycarbonate behaved in either a brittle or a ductile manner. Figure 5 shows a bimodal distribution of tensile impact results - one group being brittle and failing around 70 kJ/m² and the other being ductile with impact strength around 200 kJ/m². The two types of fractured surfaces can be compared by viewing the micrographs presented in Figure 6.

Finally, there was some indication that the age of the mouldings affected results. After testing the 43 day old samples, it was observed that for the six moulding runs the tensile impact values recorded were somewhat lower than those recorded for day one. However, after completing the testing of samples 70 days after moulding, three of the five groups recorded an increase in the average tensile impact strength compared to mouldings aged for 43 days, so that the effect of time is still uncertain and the variations noted may be due to experimental error. Consequently, it was decided that in comparing the various moulding runs all results would be considered together and no account taken of the age of the specimens at the time of testing.

Despite the above limitations, some statistically highly significant differences were evident in the resistance to stress cracking of specimens from the various moulding runs. Table 7 summarizes the production parameters which were varied between the various moulding runs and shows also the mean tensile impact strength which resulted after the stress cracking test plus a statistical comparison between the various moulding runs. Table 7 shows that for Ilexan® 121 the production parameters varied in the three moulding runs were die temperature, injection pressure and cycle time. The combination of these parameters used in run No. 6 produced mouldings with superior stress cracking resistance compared to run Nos. 2.1 and 5, ie. residual impact strength after solvent treatment was 271.3 kJ/m² compared with 196.7 and 129 kJ/m² respectively. The most likely explanation for the difference is that the higher die temperature (80°C compared with 18°C) in combination with the longer cycle time (38 s. compared with 26 to 27 s.) resulted in lower internal stress levels. The Ilexan® data sheet (8) recommends a die temperature of 71 to 93°C but some moulders prefer to use a cold die in order to reduce the cycle time and increase production rate. In comparing run Nos. 2.1 and 5 the only parameter changed was the injection pressure so that run No. 5 had a reverse profile, ie. comparatively low initial pressure to fill the die followed by a high pressure during the remaining injection hold time. This procedure caused a significant decrease in the mean tensile impact values

recorded after the stress cracking test (129.0 kJ/m^2 for run No. 5 compared with 196.7 kJ/m^2 for run No. 2.1) probably due to orientation and frozen in stresses caused by overpacking of the moulding after the initial fill. It was also significant (as mentioned previously) that the specimens from run No. 5 exhibited a bimodal distribution of tensile impact values some being low (brittle fracture) and others high (ductile fracture).

For Lexan® 101 the main production variables were the barrel temperature profile and the injection speed. In run No. 7 the minimum temperature settings given in the Lexan® data sheet [9] were used while for run No. 8 the maximum settings were used. The latter resulted in a significant decrease in the tensile impact values recorded after the stress cracking test (262.5 kJ/m^2 for run No. 8 compared with 369.3 kJ/m^2 for run No. 7) and was clearly detrimental to the environmental performance of the mouldings. However the same high temperature profile used in conjunction with a low injection speed (run No. 9) resulted in mouldings with a comparable performance to those produced by run No. 7 (357.3 kJ/m^2 for run No. 9 compared with 369.3 kJ/m^2 for run No. 7) probably due to reduced shear heating at the lower injection speed. Presumably the conditions used for run No. 7 would be preferred as less heating would be required and the cycle time was 10 s less.

3.3 No significant differences between the stress patterns of the various moulded specimens were detected when they were examined using crossed polaroids.

4. CONCLUSIONS

- 4.1 The use of a tensile impact tester to determine the residual strength of injection moulded specimens after immersion in stress cracking solutions provided a convenient means for monitoring the effect of moulding conditions on the performance of polycarbonate. However the results have a high variability necessitating the testing of a large number of samples. Consideration could be given to using a more powerful stress-cracking solution or a longer immersion time when the tensile impact machine has insufficient capacity to break the specimens and a larger test machine is not available.
- 4.2 For Lexan® 121 it was found that the combination of a heated die (80°C) and a long cycle time (38 s) produced mouldings with superior environmental stress cracking resistance compared with a cycle where the die temperature was 18°C and the cycle time 26 to 27 s. It is apparent that "quality" mouldings can be produced by the investment of a little extra time at the moulding stage.
- 4.3 The use of a reverse injection pressure profile was found to be detrimental to the environmental stress cracking resistance of Lexan® 121. This cycle involved the use of comparatively low initial pressure to fill the die followed by a high pressure during the remaining injection hold time.

- 4.4 For Lexan® 101 it was found that use of the minimum recommended barrel temperature profile resulted in mouldings with superior environmental stress cracking resistance compared with those produced by a cycle using maximum temperature settings. However if a low injection speed was used in combination with the high temperature settings then mouldings with a comparable performance to the low temperature cycle were produced.
- 4.5 The procedure outlined in this report offers a quantitative means of assessing the E.S.C. effect of chemical agents on polycarbonate or similar materials and has considerable advantages over the conventional "craze/no craze" qualitative methods.

5. RECOMMENDATIONS

- 5.1 The feasibility of this novel approach has been demonstrated but a more rigorous study should be undertaken to establish the optimum moulding conditions to be used for particular polycarbonate grades when critical components are being produced and resistance to environmental stress cracking is paramount.
- 5.2 The outlined procedure may be useful for checking whether particular chemicals or compounds have an adverse effect on polycarbonate. Batches of tension-impact specimens with high and/or low internal stress levels could be produced to aid such a study.
- 5.3 The effect of a particular annealing cycle on internal stress levels (and hence resistance to environmental stress cracking resistance) might also be monitored by this technique.
- 5.4 Since most environmental stress cracking assessments rely on static forces it would be desirable to check the correlation between those methods and the procedure outlined in this report.
- 5.5 The method offers opportunities to assess the effect of repeated contact with E.S.C. agents, contacts of various duration, and the recovery after contact (if such occurs). These are important factors which have in the past received little or no attention. Since dynamic conditions and intermittent exposures are germane - eg. recent British banning of polycarbonate crash helmets because of stress cracking by hydrocarbons - this method should be further developed.

6. ACKNOWLEDGEMENTS

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Tensile impact testing of the 'control' samples was carried out at Hoechst Aust. Pty. Ltd., and this assistance is also gratefully acknowledged.

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TABLE 1

POLYCARBONATE INJECTION MOULDING CONDITIONS

(GE LEXAN[®] GRADE 121)

Parameter	Run No.		
	2.1	5	6
Rear temp. (°C)	300	300	300
Mid temp. (°C)	330	330	330
Forward temp. (°C)	340	340	340
Nozzle temp. (°C)	330	330	330
Die temp. (°C)	18	18	80
Inj. full press (s)	0.5	1.0	1.0
Inj. dwell (s)	4	5.0	7.0
Clamp dwell (s)	20	20	30
Clamp open dwell (s)	2	2	1.0
Total cycle time (s)	26	27	38
Screw back press (MPa)	12	12	12
Inj. high press (MPa)	90	50	70
Inj. low press (MPa)	40	90	86
Mould prot. force (MPa)	8	8	8
Clamp force (MPa)	300	300	325
Inj. speed adj.	fast	fast	fast
Inj. speed selector	high	high	high
Screw speed adj. (rpm)	200	200	200
	fast	fast	fast
Screw speed selector	high	high	high

Note:-

Main variable	HP 90 MPa for 0.5 s	HP 50 MPa for 1 s	Hot die
	LP 40 MPa for 3.5 s	LP 90 MPa for 4 s	

T A B L E 2

POLYCARBONATE INJECTION MOULDING CONDITIONS

(GE LEXAN[®] GRADE 101)

Parameter	Run No.		
	7	8	9
Rear temp. (°C)	290	305	305
Mid temp. (°C)	295	315	315
Forward temp. (°C)	315	340	340
Nozzle temp. (°C)	305	330	330
Die temp. (°C)	80	85	85
Inj. full press (s)	1.0	1.0	1.0
Inj. dwell (s)	17.0	17.0	17.0
Clamp dwell (s)	30	40	40
Clamp open dwell (s)	1.0	1.0	1.0
Total cycle time (s)	48	58	58
Screw back press (MPa)	12	12	12
Inj. high press (MPa)	100	100	100
Inj. low press (MPa)	120	120	120
Mould prot. force (MPa)	8	8	8
Clamp force (MPa)	325	325	325
Inj. speed adj.	fast	fast	fast
Inj. speed selector	high	high	low
Screw speed adj. (rpm)	110	110	110
	fast	fast	fast
Screw speed selector	Med.	Med.	Med.

Note:-

Main variable

Min. Spec.
temps.

Max. Spec.
temps.

Low Inj.
speed

T A B L E 3

TENSILE TESTING - SUMMARY OF RESULTS

LEXAN® POLYCARBONATE

Property	Injection Moulding Run Nos.						Data ⁹ Bank Value
	2.1	5	6	7	8	9	
Material Grade	121	121	121	101	101	101	
Moulding Variable	Incr. H.P. Decr. L.P.	Decr. H.P. Incr. L.P.	Hbt Die	Min. Spec. temps	Max. Spec. temps	Low Inj. speed	
No. Specimens tested	5	5	5	5	5	5	
Modulus of Elasticity (MPa) (Stand. Dev.)	1501 40	1523 131	1461 57	1404 81	1431 79	1400 56	2380
Tens. Strength at yield (MPa) (Stand. Dev.)	63.0 0.2	63.9 2.5	65.5 0.6	64.6 0.2	64.6 0.1	64.5 0.1	62.1
Extension at yield (%) (Stand. Dev.)	6.9 0.2	6.9 0.2	7.2 0.4	7.2 0.4	7.4 0.3	7.3 0.2	7
Tens. Strength at break (MPa) (Stand. Dev.)	52.5 0.7	52.3 2.3	57.5 4.9	57.2 4.0	53.7 1.1	53.4 1.4	65.5
Extension at break (mm) (Stand. Dev.)	68.2 4.3	56.7 19.5	79.1 13.6	74.8 9.9	66.7 5.6	66.7 6.1	-

T A B L E 4

PHYSICAL MEASUREMENTS OF TENSILE IMPACT SPECIMENS

Moulding Run No.	Specimens Measured No.	Average Dimensions		
		Width (mm)	Thickness (mm)	Cross Sect. Area (mm ²)
2.1	15	3.14	3.24	10.17
5	17	3.14	3.25	10.21
6	5	3.14	3.22	10.11
7	18	3.14	3.23	10.14
8	10	3.14	3.24	10.17
9	6	3.14	3.24	10.17

T A B L E 5

S U M M A R Y

POLYCARBONATE (GE LEXAN®) ENVIRONMENTAL STRESS CRACKING TESTS

ASTM D1822-79 TYPE S TENSILE IMPACT SPECIMENS

IMMERSED FOR 5 MIN. IN 50:50 TOLUENE : ISO-OCTANE MIXTURE

	Moulding Run Nos.					
	2.1	5	6	7	8	9
Resin Grade	121	121	121	101	101	101
Major Variable	Decr. L.P. Incr. H.P.	Incr. L.P. Decr. H.P.	Hot die	Min. spec. temps.	Max. spec. temps.	Low inj. speed
Sample Age (d)	1	1	1	1	1	1
Mean Tensile Impact (kJ/m ²)	189.0	196.1	289.8	373.2	250.8	354.0
(Stand. Dev.)	19.4	14.0	66.7	27.2	20.7	64.8
Specimen Breaks	5/5	5/5	4/5	2/5	4/4	2/5
Sample Age (d)	7	7	7	7	7	7
Mean Tensile Impact (kJ/m ²)	236.0	148.7	279.7	384.2	262.8	379.8
(Stand. Dev.)	41.8	65.4	52.5	0.9	348	10.6
Specimen Breaks	5/5	5/5	5/5	0/5	5/5	1/5
Sample Age (d)	35	35*	* Note: This set of specimens was impact tested 7 days after solvent treatment. They have not been included in graphs or statistical comparisons.			
Mean Tensile Impact (kJ/m ²)	207.9	163.2*				
(Stand. Dev.)	26.4	49.2*				
Specimen Breaks	5/5	5/5*				
Sample Age (d)	43	43	43	43	43	43
Mean Tensile Impact (kJ/m ²)	162.8	71.5	237.6	363.4	251.1	347.1
(Stand. Dev.)	52.6	4.2	37.2	45.7	46.1	53.7
Specimen Breaks	5/5	7/7	4/4	1/4	5/5	4/5
Sample Age (d)	70	70	70	70	70	70
Mean Tensile Impact (kJ/m ²)	185.4	121.2	Not tested	351.8	282.2	334.9
(Stand. Dev.)	10.6	52.4		49.3	24.6	11.8
Specimen Breaks	4/4	4/4		4/4	4/4	2/2

T A B L E 6

STATISTICAL ANALYSIS OF RESULTS

COMPARISON OF TENSILE IMPACT RESULTS USING STUDENTS 't' TEST

(SPECIMENS TESTED AFTER 5 MIN. IMMERSION IN 50:50 TOLUENE :ISO-OCTANE MIXTURE)

Moulding Run No.	Tensile Impact (kJ/m ²)			Comparison of moulding Run Nos.	Calc. 't'	Deg. Fr. df	Probability Level
	Mean	Std. Dev.	No. results				
2.1	196.7	24	24	2.1 to 5	4.40	43	< 0.001
5	129.0	61.7	21	2.1 to 6	4.79	36	< 0.001
6	271.3	55.2	14	5 to 6	6.97	33	< 0.001
7	369.3	33.5	18	7 to 8	9.68	34	< 0.001
8	262.5	34.1	17	7 to 9	0.89	33	0.5
9	357.3	45.4	17	8 to 9	7.15	33	< 0.001

Note: The probability levels above indicate the probability of such a difference occurring by chance alone.

i.e. 0.5 probability = 1 in 2 chance = no significant difference
 0.05 " = 1 in 20 " = possible significant difference
 0.001 " = 1 in 1000 " = highly significant difference

Statistical Programme: 't' Statistic for two Means
 stat 1-30A from Hewlett Packard HP-65 stat pac 1

T A B L E 7

S U M M A R Y

MOULDING VARIABLES AND STATISTICAL COMPARISON OF
MEAN TENSILE IMPACT STRENGTH OF POLYCARBONATE SPECIMENS AFTER
5 MIN IMMERSION IN 50:50 TOLUENE : ISO-OCTANE MIXTURE

Moulding Run No.	Main Moulding Variables					Mean Tensile Impact (kJ/m ²)	Statistical Comparison (Run Nos/Prob.level)				
	Die temp. (°C)	Injection press,time		Cycle time (s)							
		High (MPa,s)	Low (MPa,s)								
<u>Lexan®</u> <u>Grade 121</u>	2.1	18	90,0.5	40,3.5	26	196.7	2.1 to 5 = < 0.001				
	5	18	50,1	90,4	27	129.0	5 to 6 = < 0.001				
	6	80	70,1	86,6	38	271.3	2.1 to 6 = < 0.001				
	Temperature Settings					Clamp Dwell Time (s)	Cycle Time (s)	Inj Speed Sel.			
	Rear	Mid	Ford.	Noz.	Die						
	(°C)	(°C)	(°C)	(°C)	(°C)						
<u>Lexan®</u> <u>Grade 101</u>	7	290	295	315	305	80	30	48	High	369.3	7 to 8 = < 0.001
	8	305	315	340	330	85	40	58	High	262.5	8 to 9 = < 0.001
	9	305	315	340	330	85	40	58	Low	357.3	7 to 9 = 0.5

Note: Refer to Table 6 for further details on statistics.

T A B L E 8

TENSILE IMPACT TESTS ON 'CONTROL' SAMPLES

(NOT TREATED WITH 50:50 TOLUENE: ISO-OCTANE SOLUTION)

Specimen No.	GE Lexan® Grade	Cross Sect. area (mm ²)	Tensile Impact			Fracture mode
			(Kgf. cm)	(J)	(kJ/m ²)	
3.17	121		50	4.9	494	Ductile
3.18	"		57	5.6	565	"
3.19	"		46	4.5	454	"
Mean		9.92			504	
Stand. Dev.					56	
7.25	101		52	5.1	503	Ductile
7.26	"		60	5.9	582	"
7.27	"		68	6.7	661	"
7.28	"		59	5.8	572	"
Mean		10.14			580	
Stand. Dev.					65	

Notes:

1. Testing completed using Zwick machine fitted with 150 Kgf.cm pendulum.
2. Specimen Nos. 3.17, 3.18 and 3.19 were from an earlier moulding run not included in this report. Moulding conditions were similar to run No. 2.1.

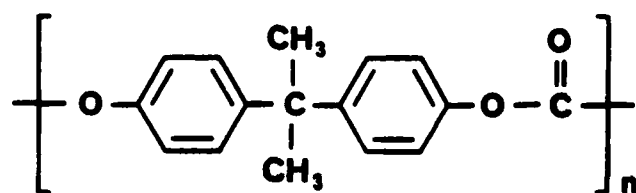


FIGURE 1 - Bisphenol-A Polycarbonate

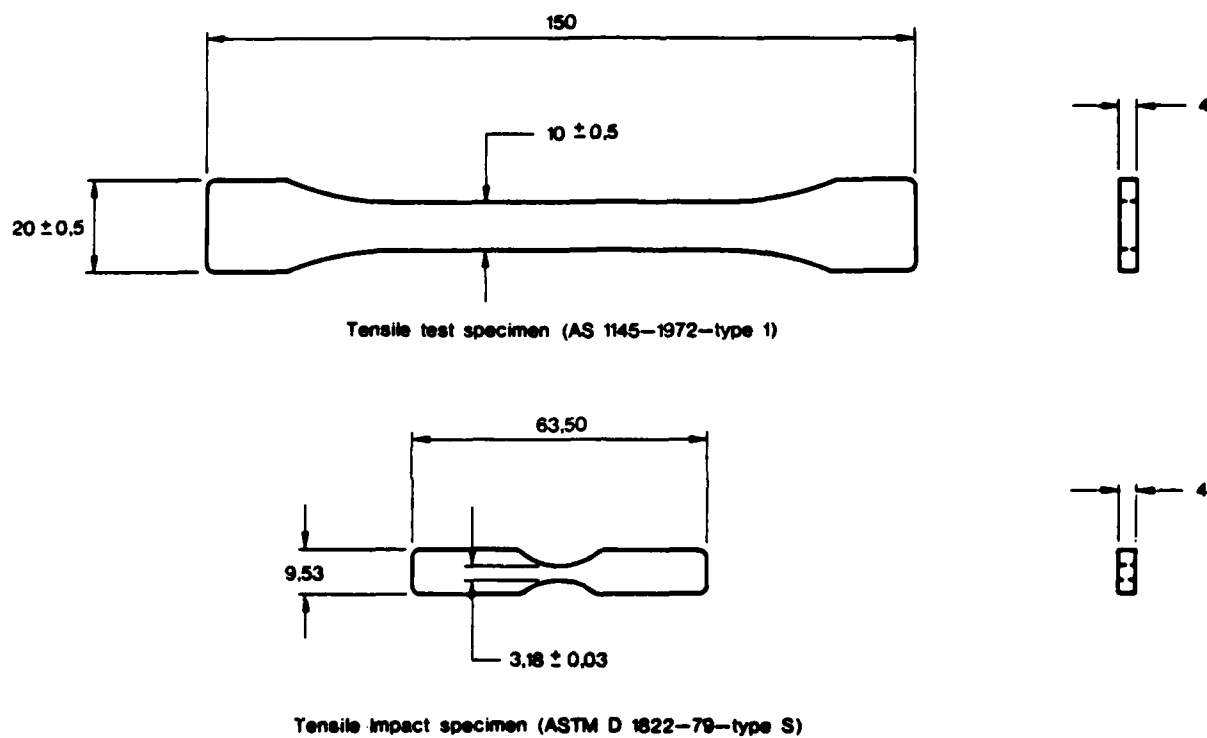


FIGURE 2 - Tensile and Tensile Impact Test Piece Configuration

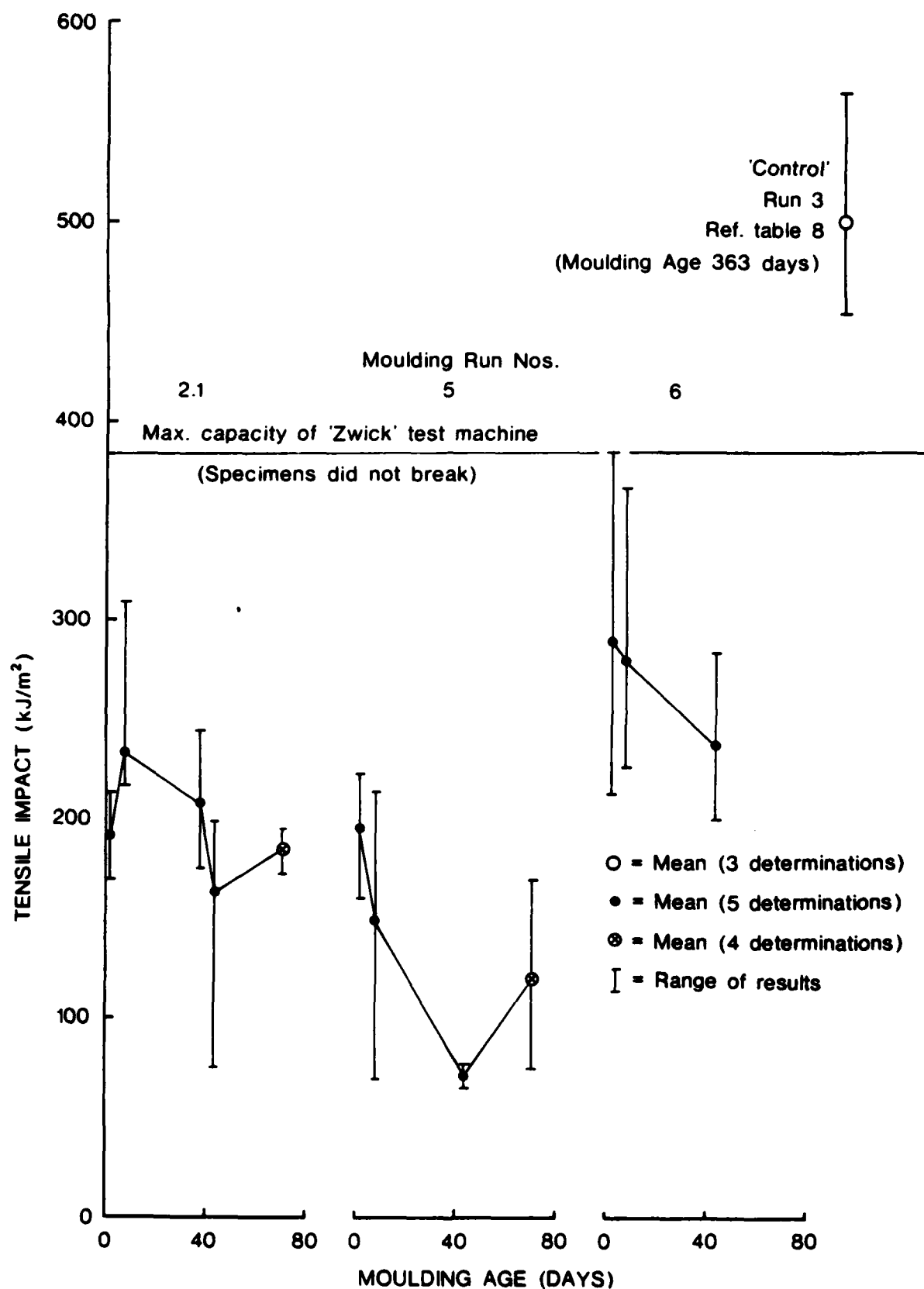


FIGURE 3 - Polycarbonate Environmental Stress Cracking Performance
(GE Lexan® Grade 121)
Tensile Impact energy after 5 min. immersion in 50:50
toluene:iso-octane solution

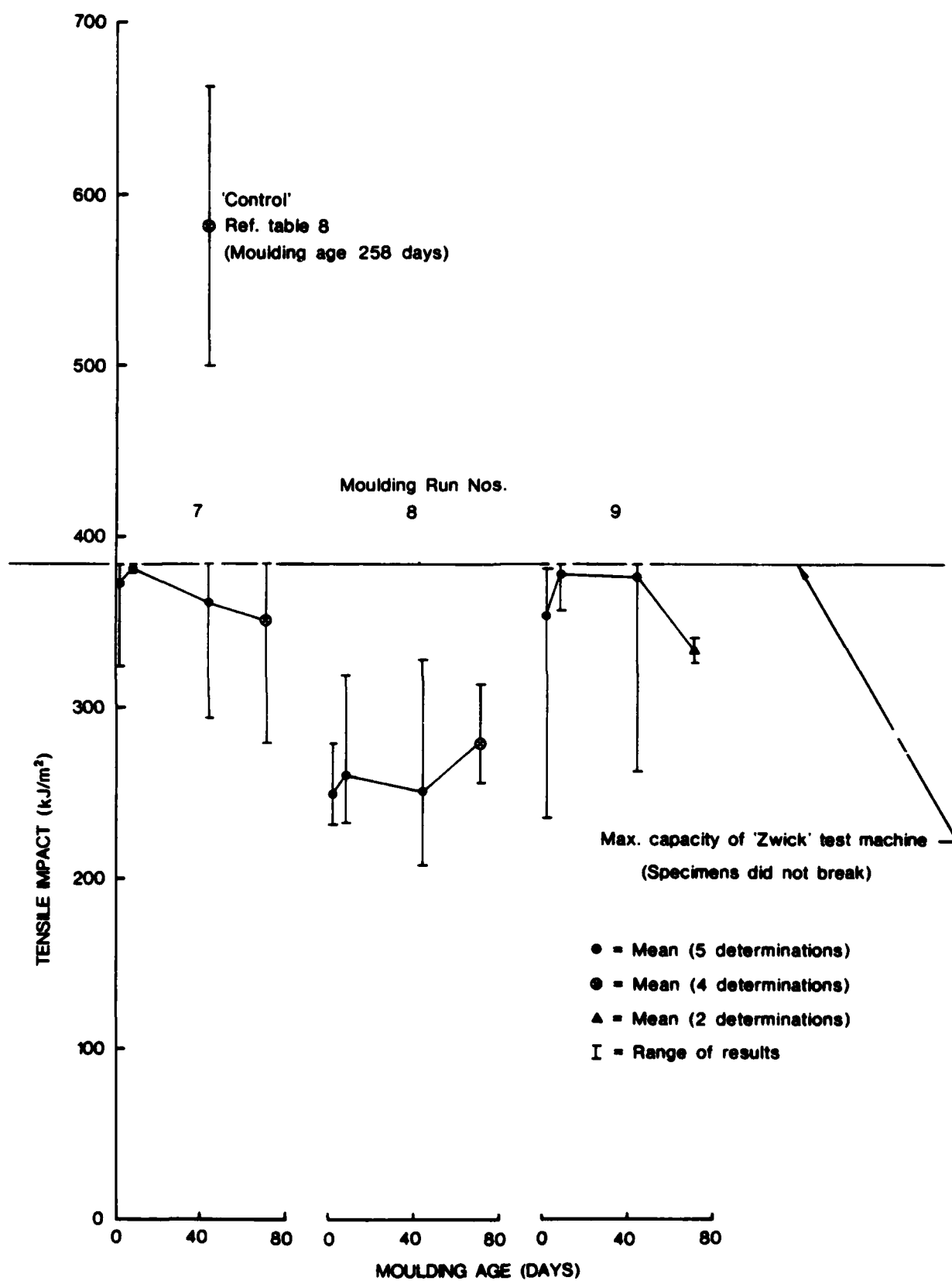
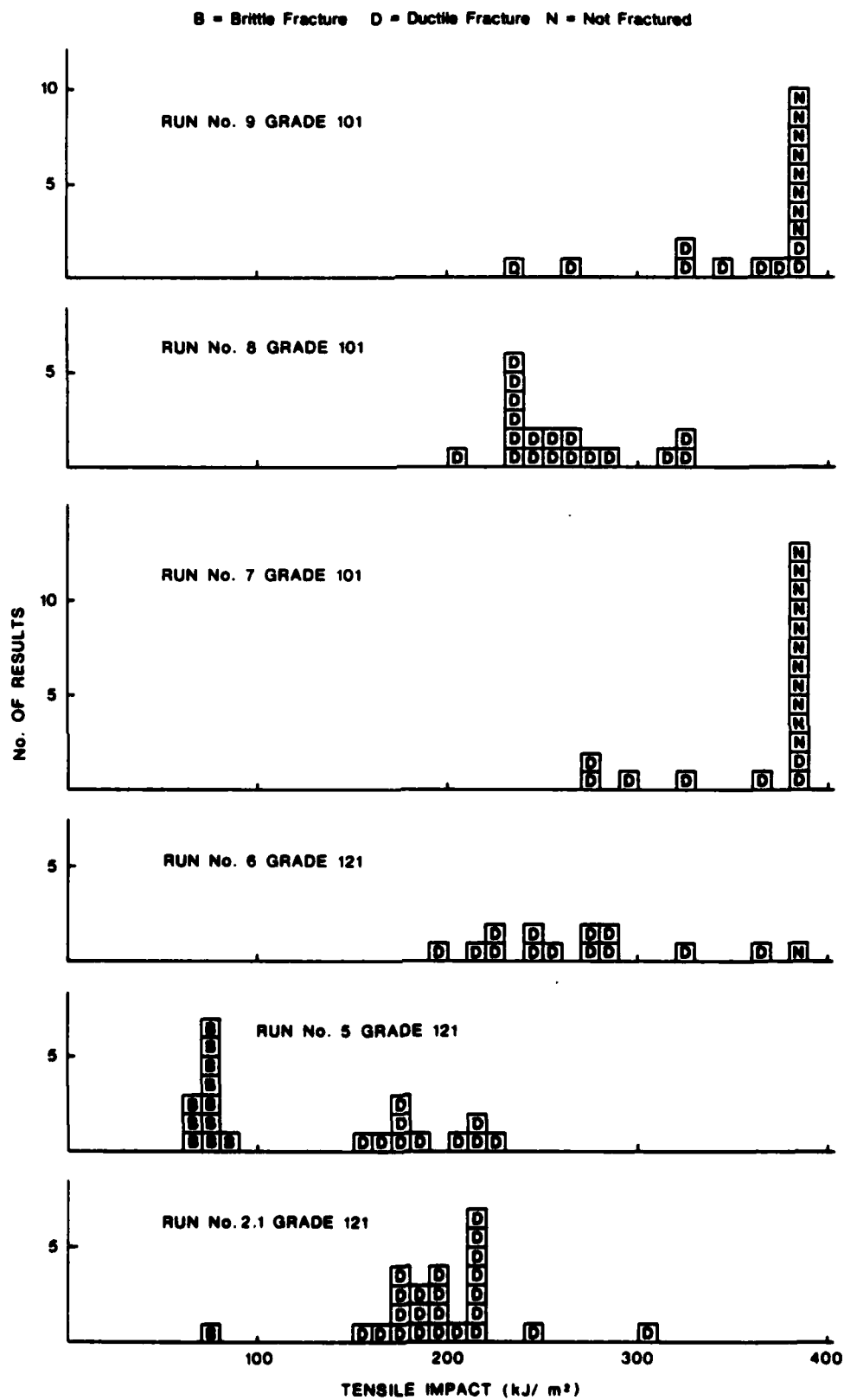
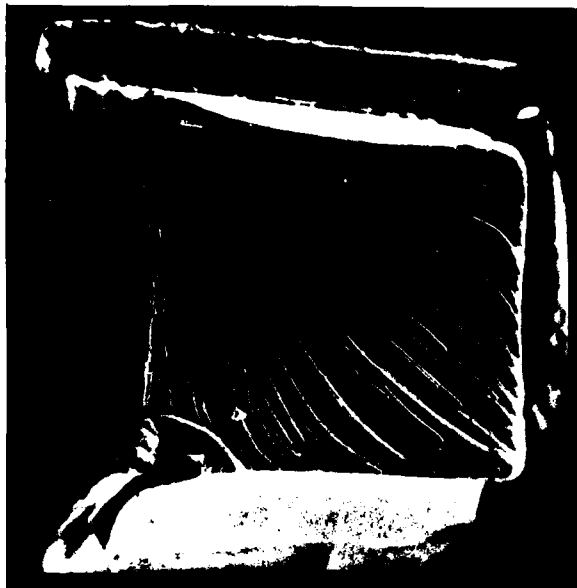


FIGURE 4 - Polycarbonate, Environmental Stress Cracking Performance (GE Lexan® Grade 101)
Tensile Impact energy after 5 min. immersion in 50:50 toluene:iso-octane solution



Specimen No. 6.8 (mag. X22) showing ductile fracture mode and necking



Specimen No. 5.16 (mag. X20) showing brittle fracture mode emanating from stress crack in top left hand corner



FIGURE 6 - Electron Micrographs of Fractured Surfaces of Polycarbonate Tensile Impact Specimens (end view)

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